AAS ‘ 93-156

SHORT ARC ORBIT DETERMINATION FOR ALTIMETER CALIBRATION AND VALIDATION ON TOPEX/POSEIDON

B. G. Williams† , E. J. Christensen , D. N. Yuan* ,
K. C. McColl* , and R. F. Sunseri*

TOPEX/POSEIDON (T/P) is a joint mission of United States’ National Aeronautics and Space Administration (NASA) and French Centre National d'Etudes Spatiales (CNES) design launched August 10, 1992. It carries two radar altimeters which alternately share a common antenna. There arc two project designated verification sites, a NASA site off the coast at Pt. Conception, CA and a CNES site near Lampedusa Island in the Mediterranean Sea. Altimeter calibration and validation for T/P is performed over these highly instrumented sites by comparing the spacecraft’s altimeter radar range to computed range based on in situ measurements which include the estimated orbit position. This paper presents selected results of orbit determination over each of these sites to support altimeter verification. A short arc orbit determination technique is used to estimate a locally accurate position determination of T/P from less than one revolution of satellite laser ranging (SLR) data, This technique is relatively insensitive to gravitational and non-gravitational force modeling errors and is therefore essentially geometrical. The quality of these short arc orbits is demonstrated by covariance analysis and by comparison to orbits determined from longer arcs of data and other tracking data types, such as DORIS and Global Positioning System Demonstration Receiver (GPSDR) data.

INTRODUCTION

For altimeter calibration and validation, precise orbits are determined for overflights of an instrumented platform located off the coast of Pt. Conception, California at the Texaco Harvest platform (lat=34.47 deg. North, long= 239,31 deg. East) and for overflights of the small islet, Lampione, located 18 km west of Lampedusa Island in the Mediterranean Sea (lat=35.37 deg North, long=1 2.32 deg. East). The goal of the orbit determination over these sites is to consistently estimate the T/Pradial position to less than a decimeter in order to detect a bias or bias drift in the radar altimeter. Since the T/P ground track repeats after 127 revolutions (about every 10 days), these sites are ovefflown by T/P

† Technical Group Supervisor, * Member of Technical S taff, Navigation Systems Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109
§ Deputy Project Scientist for TOPEX/POSEIDON Project and Member of Section Staff, Tracking Systems and Applications Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

on the same orbit within each repeat cycle. For convenience, each orbit within a repeat cycle is further divided into two equal ‘passes’, one ascending pass which crosses the equator from south to north and one descending pass which crosses the equator from north to south. Each pass is numbered consecutively from the beginning of a repeat cycle, defined as that ascending pass which crosses the equator at 99.9 degrees East longitude, so that there are a total of 254 passes in one cycle. Using these definitions, the NASA overflight of the Harvest platform occurs on ascending pass number 43 and the CNES overflight of the Lampione islet occurs on descending pass number 222 (Ref. 1).

In the context of this paper, short arc orbit determination is defined as a technique to estimate the best orbit by fitting satellite laser ranging (SLR) data over time intervals less than one revolution and typically only 10 to 15 minutes in length. This technique relies on sufficient tracking data in the vicinity of the verification site overflight to precisely determine the spacecraft altitude relative to the laser stations. For Harvest platform overflights, data may be obtained from four possible tracking stations: Quincy, CA; Monument Peak, CA; Mazatlan, Mexico; and McDonald Observatory at Ft. Davis, TX, The maximum extent of laser coverage available from these sites relative to the overflight orbit ground track for pass number 43 is shown in Fig. 1. For Lampedusa Island overflights, data may be obtained from five nearby tracking stations: Lampedusa Island; Grasse, France; Matera, Italy; Wettzell, Federal Republic of Germany; and Royal Greenwich Observatory at Herstmonceux, United Kingdom as shown in Fig. 2. The station-spacecraft visibility circles indicated in Figs. 1 and 2 represent a horizon mask of 15 degrees. Of course, on any given overflight tracking data may not be obtained from all sites due to weather outages.

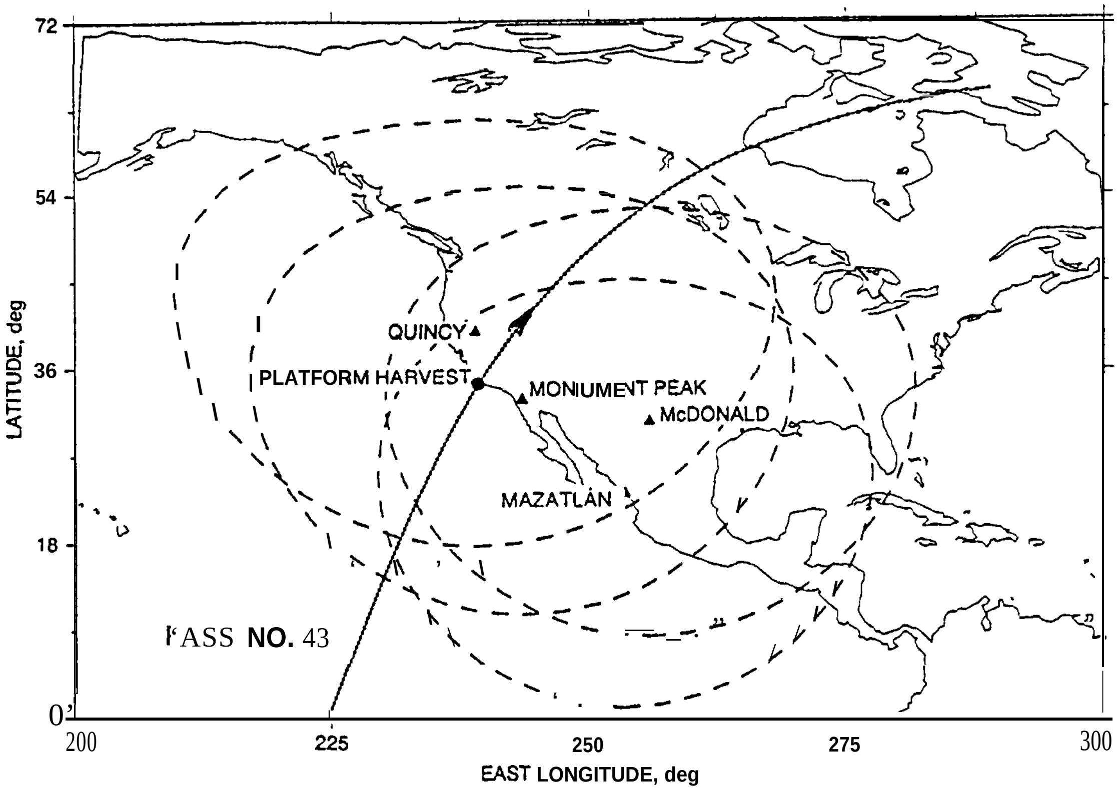

Fig. 1 NASA Harvest Verification Site Satellite Laser Ranging Coverage

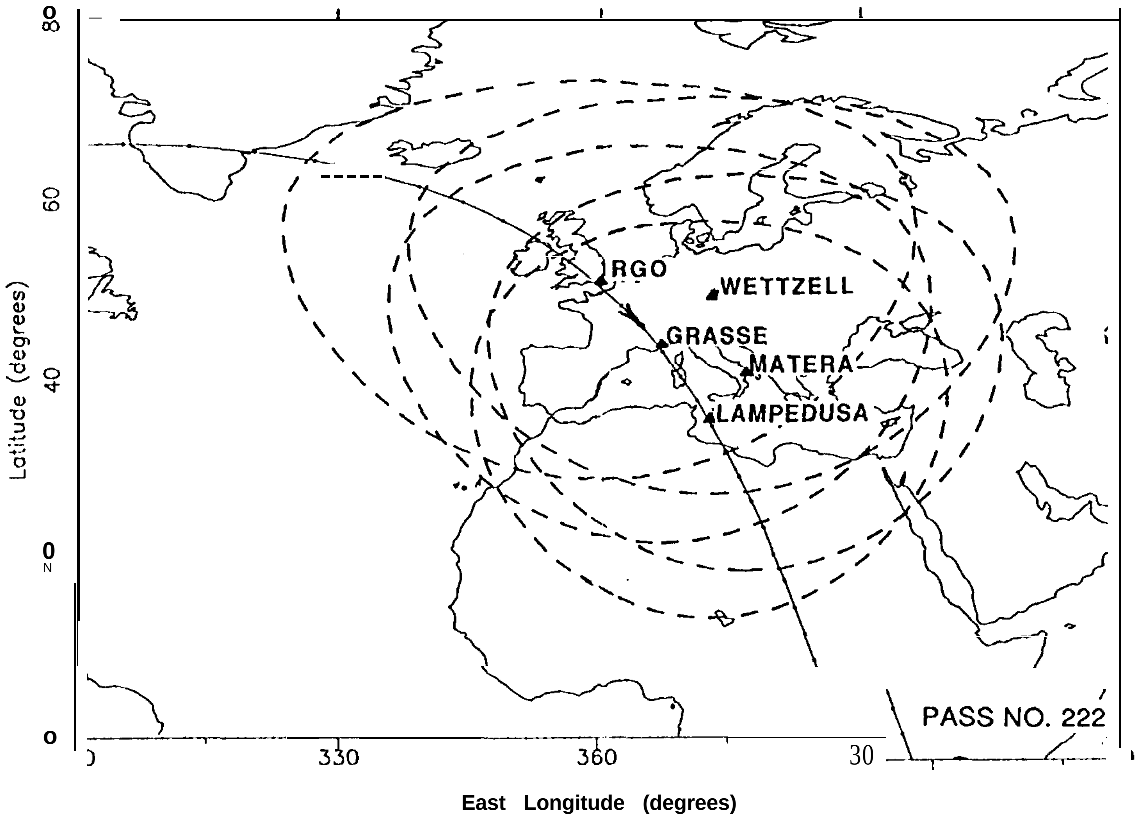

Fig. 2 CNES Verification Site Satellite Laser Ranging Coverage

The T/P short arc orbit determination capability at JPL has been developed in parallel with the T/P precision orbit determination system (PODS) processing capability at Goddard Space Flight Center at Greenbelt, Maryland, the University of Texas Center for Space Research at Austin, Texas and the Colorado Center for Astrodynamics Research at Boulder Colorado. The JPL development team has been aided by, and has participated in, specific model improvements for T/P PODS. Specific non-gravitational forces acting on the TOPEX/POSEIDON spacecraft are simulated by simplifying the complex shaped spacecraft body and solar array into an eight plate box and wing model [2]. The box-wing model is oriented as a function of orbit angle and the inclination of the Sun to the orbit plane in order to mimic the nadir pointing, yaw steering and solar array pointing of the T/P spacecraft.

The non-gravitational spacecraft forces modeled include those due to atmospheric drag, solar pressure, Earth radiation pressure (both visible and infrared), and thermal radiation from the box-wing due to solar heating and internally generated heat. Additional empirical forces due to gas leaks and periodic accelerations (once- and twice-per-revolution) may also be modeled. These empirical force models are especially useful for the short arc technique as will be demonstrated below. Parameters which scale each force may be estimated as necessary. Modeled gravitational effects include point mass accelerations from the planets, Sun and Moon, relativity, Earth and Moon oblateness, and solar and lunar Earth tides.

DESCRIPTION OF SHORT ARC TECHNIQUE

Previous analysis has shown that to minimize effects of mis-modeled forces on the spacecraft it is advantageous to perform the orbit determination over SLR data arcs as short as a single tracking pass (from horizon to horizon) from laser tracking stations located near the verification site[3]. For the two T/P verification site overflights, these data arcs are at most 15-20 minutes long. However, tracking outages, usually caused by obscuration of the laser by clouds, during the overflight can reduce coverage and thereby significantly reduce the accuracy of the estimated orbit, It was determined that at least two tracking stations are required to give sub-decimeter determination of the radial position at overflight, and covariance analysis results are presented below for the most favorable station combinations.

The short arc technique uses a batch filter strategy over each short arc to estimate the spacecraft position, velocity and a set of constant accelerations at epoch. These constant acceleration estimates over such a short data arc effectively remove residual force modeling errors whenever there is sufficient tracking data. The constant acceleration components may be estimated in radial (R), transverse (T) and normal (N) unit directions which are defined in terms of the Earth-centered, Space-fixed, J2000 position and velocity vectors as follows:

$$\hat{R} = \vec{r} / \|\vec{r}\|, \quad \hat{N} = (\vec{r} \times \vec{v}) / \left\|\vec{r} \times \vec{v}\right\|, \quad \hat{T} = \hat{N} \times \hat{R}$$

Two strategies for estimating the empirical forces are investigated in this paper: one which estimates two orthogonal components in the transverse and normal directions, and another which estimates all three orthogonal components in the radial, transverse and normal directions. The reason for eliminating the radial force in one strategy is to test the sensitivity of the estimated orbit to a force which effectively rescales the gravitational acceleration of the Earth. Results show that estimating the radial component of constant force gives an average radial position bias of 1 to 2 cm lower over Harvest.

Since short arc orbit accuracy is most sensitive to the accuracy of geometric models used in the orbit determination procedure, particular attention was given to modeling the ground station coordinates, solid Earth tides, tropospherical range correction, Earth rotation and polar motion parameters, spacecraft center of mass offset from the laser retro-reflector assembly (LRA), and spacecraft orientation. The T/P box-wing model mentioned above was used to model the orientation of the LRA relative to the spacecraft center-of-gravity; however, the forces predicted by the box-wing model were not used in the final short arc technique. Essentially, error in the box-wing acceleration model has to be removed by estimating scaling coefficients anyway, and the empirical force model can completely replace the box-wing accelerations over the short arc by adequately fitting the orbit with less computational overhead. Either approach results in the same radial position estimate for the short arcs to within a centimeter, This also appears to be the case for longer arc orbit determination as long as sufficient tracking data is available

COVARIANCE ANALYSIS RESULTS

A covariance analysis was performed for the verification overflights at Harvest to indicate the best tracking geometry and the limiting error sources for short arc orbit determination. The assumptions for this analysis are presented in Table 1. To give a realistic sense of the relative station-to-station location uncertainty, a correlated SLR station location covariance matrix was used that was derived from combined solutions from May 3rd, 4th and 5th of the 1989 GPS GEOMEX campaign[5]. The formal standard deviation on each SLR station position from this ground survey was about 3 to 5 cm in all three components.

The position uncertainty for overflights of Harvest was computed for combinations of stations using a batch filter which included model parameters that are not estimated but which do influence the final estimate covariance by their uncertainty. These 'considered' parameters represented the model errors in solar pressure and drag, Earth's gravity field, station locations, and troposphere while using the standard deviations indicated in Table 1. A plot of radial position error and the relative influence of the considered model parameters for a particular pair of stations, Quincy and Monument Peak, is shown in Fig. 3. The behavior shown in this plot is typical of all the combinations studied. The main feature of all these cases is the position of the minimum error near the time the orbit passes over the tracking stations. Note that the minimum is slightly after the Harvest overflight in Fig. 3, and this is typical of the other cases. The predicted total radial error at Harvest overflight for the best of the *two* station tracking cases is presented *in* Table 2. The other two station combinations had radial uncertainties above 10 cm and are not shown. In addition, the case for all four sites tracking yeilded 3.22 cm radial error at Harvest, although the minimum error of about 2 cm occurred further inland. This indicates the importance of accurate station location estimates, since the relative station location error tends to outweigh the additional information from the extra tracking stations, at least when compared to the Quincy - Monument Peak pair. However, in practice it is recognized that covariance analysis gives an idealized result, and hence the difference is not significant enough to warrant excluding any of the already sparse data from our fits by fitting only station pairs.

Table 1
COVARIANCE ANALYSIS ASSUMP'J'1ONS

SLR DATA NOISE:	
	2 cm for Quick-Look Norma Pts.
A PRIORI STANDARD DEVIATIONS:	
TOPEX Orbit:	3 m in position
Gravity:	Lumped-sum diagonal from GEM-T2
Non-Conservative Forces:	Solar Pressure 20%
	Atmospheric Drag 20%
Station Locations:	Correlated Covariance from GPS survey[5]
Troposphere:	Wet and Dry Zenith Delay 0.2 cm

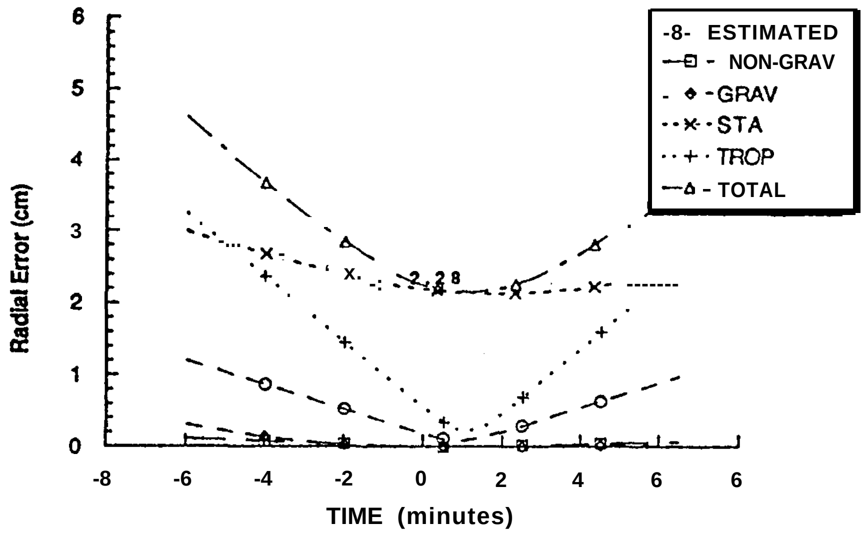

Fig. 3 Predicted Radial Error at Harvest for SLR Tracking From Quincy and Monument Peak. Overflight of Harvest Occurs at Time = O.

'I'able 2
PREDICTED RADIAL ORBIT ERROR FOR TWO STATIONS TRACKING AT HARVEST OVERFLIGHT (cm)

	Mon. Peak	McDonald	Mazatlan
Quincy	2.28 cm	2.32 cm	2.62 cm
Mon. Peak	--	3.57 cm	3.13 cm

Another feature of Fig, 3 is that the dominant error source is the 'geometric'-type errors due to uncertainty in station locations and tropospheric delay, with station location error being the largest. The curve labeled 'estimated' in Fig. 3 shows the portion of the total error attributable to the assumed data noise. It is the next largest contributor after the geometric error contributions. Note that the 'dynamic'-type errors due to uncertainty in gravity harmonics and non-conservative force models are smallest, and are not a factor in determining the orbit radius at the time of overflight. These features were common to the covariance analysis for the other station combinations, This behavior shows the essential geometric quality of the short arc orbits.

Covariance analysis results show the best orbit position determinations over the verification sites are obtained when two or more stations simultaneously range to T/P at the time of overflight and they are distributed on both sides of the satellite ground track. Unfortunately, as seen in Fig. 2, the available tracking stations for Lampedusa overflights are all located on the east side of the pass number 222 overflight so this geometric advantage is not present. Analyses also indicated, however, that a tracking site directly under the ground track will produce good position determination and for this reason CNES temporarily placed a SLR station on Lampedusa Island. There was also some discussion of placing an SLR site at Vandenberg Air Force Base to supply tracking directly under the pass 43 ground track for the NASA verification site, but this was not done due to SLR system availability and budgetary considerations.

ORBIT DETERMINATION RESULTS FOR ALTIMETER VERIFICATION

The laser ranging actually obtained from the tracking stations at the two verification sites is presented in Table 3. In the table, an 'x' indicates if any SLR quick look normal point data was obtained from a given station on a particular repeat cycle. The T/P orbit was maneuvered into the repeat orbit and cycle one was started on September 23, 1992. The first NASA overflight occurred on September 24, 1992 followed by the first CNES overflight on October 1, 1992. The table shows tracking coverage by station up to cycle 13 for the Harvest overflight on January 21, 1993 and up to cycle 8 for the Lampedusa overflight on December 10, 1992. A dashed entry in the table indicates the tracking station was removed. Note that no overflight tracking was obtained for Harvest on cycle 11 nor for Larnpedusa on cycle 7 due to SLR system problems and weather outages. Also note the lasers at Lampedusa and Mazatlan were removed after cycles 8 and 11, respectively. There were only two overflights, cycles 3 and 4, over Lampedusa that had more than single station tracking which included the Lampedusa laser, so these were the only overflights which produced useable short arc orbits.

This paper deals primarily with the first thirteen overflights of Harvest. Of these thirteen, only nine resulted in useable orbits. The overflight for cycle 1 was not processed since there was no altimeter data, the overflights for cycles 4 and 11 lacked sufficient tracking data, and the overflight for cycle 6 had SLR problems at two stations that made the data unusable. Table 4 shows the sample mean and standard deviation of the difference between short arc orbits compared to orbits determined from longer arcs of data and other tracking data types. The table includes entries for short arc orbit determination both with and without a radial constant acceleration estimate as mentioned earlier. The mean height

Table 3
SLR TRACKING DATA COVERAGE FOR VERIFICATION OVERFLIGHTS

Harvest Overflights:

	Cycle Number												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Quincy	x	x	x		x	x	x			x			
Mon. Peak		x	x	x	x	x		x	x	x		x	x
McDonald	x	x	x			x	x	x	x			x	x
Mazatlan		x	x				x	x		x		--	--

Lampedusa Overflights:

	Cycle Number												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Lampedusa	x		x	x					--	--	--	--	.-
Matera					x								
Grasse			x			x		x					
Wettzell		x											
RGO			x	x									

Table 4
Estimated Orbit Height at Harvest Compared to Longer Arc Orbit Determination Strategies (not including cycle 6 overflight)

Transverse, Normal Empirical Forces Estimated

comparison Orbit:	Mean Height Difference (cm)	Std. Dev. (cm)
10 day SLR fits	-0.1	4.0
10 day-DORIS fits	1.6	3.6
1 day GPS fits	4.4	4.0
Combined	1.8	4.4

Radial, Transverse, Normal Empirical Forces Estimated

comtxt.risen Orbit:	Mean Alt. Difference (cm)	Std. Dev. (cm)
10 day SLR fits	1.6	5.2
10 day DORIS fits	3.4	4.3
1 day GPS fits	6.2	3.2
Combined	3.5	4.8

difference in Table 4 is defined relative to the short arc orbits such that a positive mean altitude difference indicates the longer arc fits are estimating a higher overflight and that the short arc fits are estimating a lower height over Harvest. The short arc orbits are 1 to 2 cm lower in the mean when using the strategy that estimates a constant radial acceleration. Note that the standard deviation is less than about 5 cm for all comparisons in Table 4. When comparing the two Lampedusa overflights to the longer arcs, the difference in mean was about -30 cm for cycle 3 and about +40 cm for cycle 4, so the results there are much less conclusive.

Table 5 presents a summary of the nine Harvest overflights and two Lampedusa overflights as determined from the short arc strategy that estimates only the transverse and normal constant accelerations. The table includes the estimated time of overflight, ground track miss distance, height at closest approach, and the number of SLR quick look normal points and root-mean-square of the fit. The ground track miss distances are given in meters either to the southeast or northwest for Harvest. As seen in the table, the overflights at Lampedusa actually occur about 18 km to the southwest over the Lampione rock. The height at overflight is computed from the orbit radius by using the T/P standard reference ellipsoid which has an equatorial radius of 6378136.3 km and l/f = 298.257 as the flattening factor. Also evident in the table is the large rrns of fit for the cycle 6 overflight of Harvest which was caused by SLR tracking system problems. The estimated orbit from this fit was not considered reliable enough to predict the position and height of the overflight, so these values were omitted from the table for overflight 6. Note that exclusive of the cycle 2, 3 and 6 fits, the residual rrns of fit for the remaining short arcs is less than one centimeter for Harvest.

Table 5
SHORT ARC ORBIT DETERMINATION OVERFLIGHT SUMMARY

HARVEST OVERFLIGHTS

Cycle No.	Time of Overflight (UTC)	Ground Track Closest Approach (m)	Height @ Closest Approach (m)	No. SLR Points	RMS of fit (cm)
2	10/04/92 17:37:45.28	263.535 se	1344941.507	99	1.47
3	10/14/92 15:36:14.33	1061.666 se	1344959.910	77	2.44
4	10/24/92 13:34:46.26	706.482 se	1344956.807	23	0.54
5	11/03/92 11:33:18.30	334.762 se	1344974.342	45	0.36
6	11/13/92 09:31	--	--	96	5.79
7	11/23/92 07:30:22.23	71.657 nw	1344991.546	38	0.46
8	12/03/92 05:28:53.64	11.326 nw	1344985.426	67	0.82
9	12/13/92 03:27:24.78	49.876 se	1344976.579	73	0.67
10	12/23/92 01:25:55.90	55.509 se	1344957.392	86	0.66
11	1/01/93 23:23	no fit	no fit	0	
12	1/1 1/'93 21:22:59.81	165.050 nw	1344893.861	75	0.40
13	1/21/'93 19:20:31.46	91.242 nw	1344866.365	54	0.67

LAMPEDUSA OVERFLIGHTS

Cycle No.	Time of Overflight (UTC)	Ground Track Closest Approach (m)	Height @ Closest Approach (m)	No. SLR Points	RMs of fit (cm)
2	10/21/92 14:54:30.99	18062.291 SW	1345129.869	58	3.42
3	10/31/92 12:53:92.98	18237.049 SW	1345156.246	37	4.12

SUMMARY

The results shown in this paper indicate that short arc orbit determination using satellite laser ranging data can be used to estimate orbit position relative to a local tracking network. The covariance analysis and results at Harvest show that short arc orbit determination accuracy depends primarily on favorable tracking geometry and is relatively insensitive to mismodeled spacecraft dynamics. For the Harvest overflights, the technique requires a minimum of two tracking stations which should be located on either side of the ground track to obtain the best determination of orbit height. In addition, covariance analysis indicates station location error is the limiting error source for determining orbit height at Harvest by the short arc technique.

The short arc technique used here relies on a 'relaxed-dynamic' orbit determination approach which estimates spacecraft position, velocity and empirical forces at epoch to reduce the influence of spacecraft force modeling errors. The estimates of components of a constant empirical force tend to absorb any force mismodeling biases over the ten to twenty minute tracking arc in a manner consistent with the laws of motion, so that a geometric or triangulated position determination is made. Two different combinations of empirical force estimates were tried, one which estimated only tangential and normal force components and another which estimated radial, tangential and normal force components. The effect of estimating the radial force component was art average orbit height adjustment of about 1 to 2 cm (lower) radially at Harvest.

A comparison was made between the short arc orbits determined from satellite laser ranging and orbits determined over arc lengths of one to ten days using either SLR, DORIS or GPS tracking data. Orbits determined from long arcs of each of these data types were determined by the same 'dynamical' fit technique which relies on precise models for spacecraft accelerations. When compared to orbits determined over the longer arcs, the short arc orbits at Harvest tend to have lower mean altitude regardless of data type used. The largest mean altitude difference of 5 to 6 cm at Harvest occurs when comparing orbits determined from GPS tracking. A similar mean radial offset also exists between the long arc SLR and DORIS orbits and GPS orbits.

The radial bias relative to the SAO orbits is believed to be due primarily to long period dynamic effects present in the longer arc determinations that do not affect the short arc orbits because of the geometrical nature of the technique. However, some part of the radial bias may also be due to various geometrical differences such as non-uniform global tracking distribution, station coordinate offsets, phase center offsets (i.e., the geometrical point to which the SLR, DORIS or GPS observable is referenced), media effects, etc. Each of these is an area for further analysis and will continue to be investigated by the authors and other orbit determination specialists using a variety of long and short arc fitting techniques.

For the Lampedusa verification site overflights, short arc orbit determination was hampered by insufficient laser tracking data. Only two overflights obtained enough tracking to try the short arc technique. After cycle 8, the laser station at Lampedusa was removed and there is no plan to replace it, so any further altimeter calibration and validation activities there will have to depend on long arc orbit determination.

ACKNOWLEDGEMENTS

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The comparison orbits determined from GPS tracking were provided by J. R. Guinn of JPL's GPS Data Processing Facility.

REFERENCES

1. TOPEX/POSEIDON Joint Verification Plan, Jet Propulsion Laboratory, California Institute of Technology, JPL Publication 92-9, July 15, 1992.

2. **Marshall, J.** A., S. **B. Luthcke, P. G. Antreasian and G. W. Rosborough,** 'Modeling Radiation Forces Acting on TOPEX/POSEIDON for Precision Orbit Determination", NASA TM 104564, June 1992.

3. Guinn, J. R. and E. J. Christensen, "TOPEX/POSEIDON Altimeter Calibration Using Short Arc Orbit Determination Over Point Conception, California", presented at AGU Spring Meeting, Baltimore, MD., May 30, 1991.

4. Christensen, E. J., B. G. Williams, **D. N. Yuan, and** K. C. McColl, "Modeling Non-Gravitational Forces Acting on TOPEX/POSEIDON: The Early Days", Paper AAS 93-155 presented at AAS/AIAA Spaceflight Meehanics Meeting, Pasadena, CA, February 22-24,1993.

5, Born, G. H., Personal Communication, Colorado Center for Astrodynamics Researeh, University of Colorado, Boulder, Colorado.